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Water Conservation Optimisation For Building Drainage Systems

Dr. D. P. Campbell

Abstract— **An assessment of the impact of water conserving fixtures and fittings in typical housing development subject to water conservation measures is conducted. A range of 25 different house styles were simulated with a diversity (random usage) profile based on appliance type and site investigation. The simulation was conducted by DRAINET, a simulation engine based on the Method of Characteristics and a finite difference scheme validated through field studies. Simulation results show that water conservation down to 80% of non-conserved levels did not significantly reduce the solid transport capability of the associated waste water collection system. At 60% of non-conserved levels, there was a marked reduction in the solid transport capability of the waste water collection system. The use of a small (14 litre) intermittent discharge tank (tipping tank) is suggested as a means of extending safe water conservation practices. The tipping tank option would be the best value and fastest technology to implement as a retro-fit option or as a feature in new-builds. Using only approximately 10% of the water conserved, this measure is effective in maintaining solid transport down to 60% of non-conserved levels, which is significantly lower than current water conservation initiatives are achieving.**

Index Terms— **Water conservation; mathematical model; tipping tank; solid transport; wastewater collection system; building drainage.**

I. INTRODUCTION

The basic premise of this research is that the maximum water conservation factor achievable is unlikely to be the optimum water conservation factor [1] ,[2] , because removing blockages and mitigating lower water quality are likely to emit more carbon than was saved from the water that was conserved.

The findings from the work in this paper are that water conservation down to 80% of current capacity can be safely achieved, while water conservation below 60% of current capacity is likely to cause widespread issues related to increased sewer blockages. It may also result in altered sewage characteristics reaching treatment plant, arising due to slower transport rates (i.e. greater residence times). The use of tipping tanks is suggested as a means of safely achieving water conservation to 60% of current capacity. Between 80% and 60%, there will be regional variations in the fate of the waste water system, which fall beyond the scope of this work. This is clearly serious and the work summarized here is timely because current policies are aimed at achieving the maximum possible reduction in water use.

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II. SIMULATION MODEL (DRAINET)

2.1 DRAINET Description

The main tool in this research is a computer simulation package known as DRAINET. DRAINET is an integrated modelling package authored in C++. Using DRAINET it is possible to analyse the performance of drainage systems by conducting sensitivity analyses, thereby determining 'performance envelopes'. The aim would be to predict, for example, how little water could be used in a given system if the pipe diameter was reduced or, perhaps, the slope was increased. In the longer term this would be used to influence building regulations to minimise future maintenance problems while, at the same time, encourage water conservation.

DRAINET is based on a finite difference scheme and utilises the method of characteristics as a solution technique to simulate drainage system operation. This is done via the equations that define unsteady partially filled full bore pipe flows and the boundary conditions represented by pipes, junctions and other common system components. In the case of fixtures and fittings, these have to be measured in the laboratory so that their accurate discharge characteristics in terms of flow rate against time can be employed in simulations.

DRAINET has been developed continuously since the late 1980's through several large EPSRC grants. Most of the work concerned the definition of the relevant boundary equations to describe the behaviour of water and/or air [3], [4], [5] in circular drainage pipe systems including junctions and joining flows. The legacy of this work in the form of a large physical test system has been applied to the work summarised in this paper. Understandably, much research was devoted to the behaviour of solids in live drainage systems [6].

Discharge of waste solids into a drainage system is due to discharge from a wc which produces a surge wave, discharging the solid into the drainline. The inclusion of the surge in this scenario requires a modelling technique capable of predicting the attenuation of a surge wave along a pipe. The method most suited to this is the solution of the St.Venant equations of momentum and continuity in a finite difference scheme through the method of characteristics. Physical attributes of the system, such as entry and exit conditions, pipe junctions, slope defects and obstructions are easily catered for by the inclusion of empirical boundary equations which describe their effect on the water [7], [8], [9]. The method of characteristics is very effective at predicting the attenuation of waves along a pipe, but it has not been shown to easily include a moving boundary condition suitable for the description of solid objects moving through the system at a velocity differing from that of the water.

The most significant existing model in terms of its usability and accuracy is due to McDougall [8] . This model was initially developed to describe the effects of pipe slope defects on solid transport, however some inconsistencies were highlighted in existing models leading to the development of a more robust model. McDougall's enhancement to the DRAINET model is based on the relationship between the flow velocity (Vf) and the velocity of the solid (Vs) . This relationship between (Vf) and (Vs) is capable of tracking the velocity of a solid under many flow conditions, the velocity of the solid decreasing with decreasing flow velocity and *vice versa*. This method works well, however it has deficiencies, the presence of the solid does not modify the surrounding water conditions, the solid does not exist within the flow represented in the model, it is in effect a virtual solid. The consequences of this in terms of describing the interaction of solids is quite significant. If the water conditions are not modified to account for the presence of a solid then the modification of the velocities of approaching solids would need to be described in a way that covers a very wide range of interaction scenarios. However McDougall's technique exists and fills a gap in simulation capability.

In use, a simulated system, hypothetical or representing a real-life system, can be built up via a reasonably intuitive graphical user interface using a combination of icons representing pipes, junctions and sanitary appliances etc., assembled schematically to represent the system. Parameters such as friction, slope, pipe element length, junction type, base flow, appliance discharge profile and the presence of solids, either in a flush or at strategically pre-determined locations, are all user selectable. The output is both by visual real-time representation of flow depth and solid position at any network node or nodes, and by .csv tabular values for more in-depth analysis as was used in this investigation. Typically, the user will visually narrow down the conditions until the point of interest is reached, then proceed by digital data analysis.

The model, although it still has some limitations, allows systems to be modelled for single or multi-storey networks hence allowing any potential problems to be foreseen and dealt with prior to construction. In this respect, DRAINET is a sensitivity analysis or design tool, rather than a CAD package. In order to change the regulations however a concrete argument must be formed showing that the new method of designing drainage systems is reliable. The purpose of this paper is to report the outcome of a simulation based on live site data to provide a basis for such an argument.

2.2 Case Study – Waulkmill Residential Development, Scotland

Data to construct the model was based upon the digital water use records provided by Scottish Water on the Walkmill Residential Development, Paisley. The most effective way in which to conduct the analysis was by modelling the housing development and producing a sensitivity analysis from it. This was based on a comparison between 100% normal usage, 80% usage, 60% usage, and 60% usage with the addition of a tipping tank.

With the hydraulic and housing layout information of the development already provided by Scottish Water in the form of a GIS map (Figure 1(a)), the system could be modelled in DRAINET.

Figure 1(a) GIS survey map of the physical test site: Waulkmill Development, Paisley, West of Scotland. Area simulated is shaded.

The site consists of a number of streets, however, for the purpose of this investigation, only one street was digitised as this was sufficient to demonstrate the dependence of flow conditions on water conservation activities. The street selected is highlighted by the shaded region in Figure 1(a) and expanded in Figure 1(b). Since each such development in the UK will have widely different conditions, an exhaustive catalogue of successes and failures was beyond the scope of the objective of this paper.

Figure 1(b) Expanded view of the area simulated in the Waulkmill Development.

To begin the DRAINET simulation, the house types were categorised in order to reduce laborious, repetitive sub-model creations. The site consists of approximately 100 houses ranging from bungalows, detached and semi-detached properties. By separating the houses into these three categories, a template model of each within DRAINET can be replicated as required. Figure 1(c) shows a typical schematic representation of a two-house semi-detached unit: note that there is no scale in the representation. Drainet was then used to perform a sensitivity analysis which produced results on: solid transportation, pipe water depths and pipe flow at varying times during the simulation.

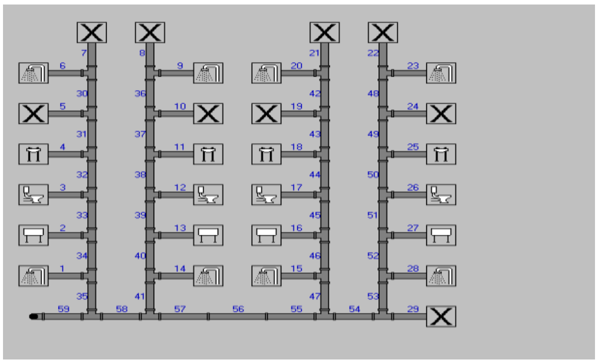

Figure 1(c) Screen picture from DRAINET of the schematic representation of a two-dwelling cluster as part of the simulated area

2.3 Diversity Factor: Appliances and Characteristics

The simulations required appliance timings or diversity factor, and this was generated by using random data applied to the houses in the area simulated. The number and type of appliances were available from the developer and could be linked to house number on the street. By interviewing residents, a reasonably accurate representation of occupancy for the houses was established, and the randomised usage data was applied to this crude data. Table 1 illustrates the diversity factor template used in the simulations. A large database of appliance type discharge profiles has been accumulated by the author over several decades including basins, sinks, showers, w.c.'s, baths and white goods. This was expanded for the purposes of this investigation by purchasing a representative example of the w.c.'s installed in the Walkmill development. While some may have been changed in the nine years since it was occupied, the effect was judged to have little impact on the gross findings.

2.4 Determining Tipping Tank Flow Profile

Heriot-Watt University developed a method of calculating the discharge profiles of appliances in 1996. Figure 2 illustrates how the volume versus time graph is obtained by a system of depth measurement at a range of locations corresponding the principal nodes and antinodes of the first three degrees of freedom over the surface of the collection tank[10] .

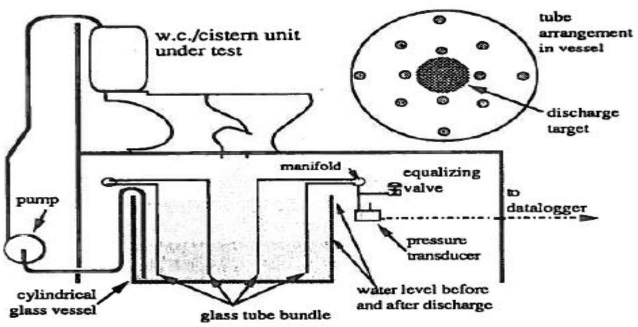

Figure 2 Schematic representation of the discharge characteristics measuring device used in this research

A pressure transducer records the average air pressure in 12 vertical tubes distributed across the surface of the tank caused by changes in the rate of water surface height. The output has very good sensitivity and immunity from noise, permitting the detection, for example of the difference between a 6 litre clean flush of a w.c. and the same w.c. with 12 sheets of toilet paper included. This allows progress in improving models of drain loading and w.c. fluid contamination removal [11]. Figure 3 shows the discharge profile of the 20 litre tipping tank used, which had a repeatable useable volume of 14.1 litres.

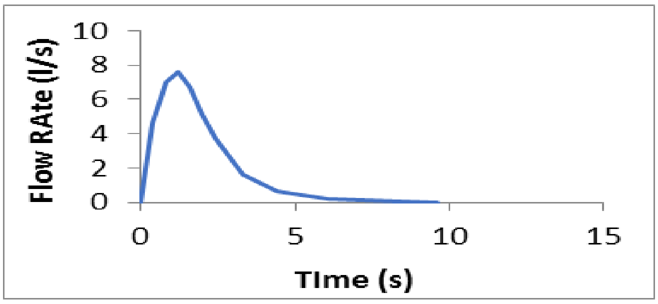

Figure 3 Measured tipping tank profile used in this simulation

The aim was to utilise a small fraction of the water saved cumulatively from the terraced housing to operate the tipping tank, thereby achieving the majority of the water savings which would still be far in excess of that which would be considered safe. The tipping tank would be strategically placed so that solids entering the communal sewer pipe are downstream from the tank discharge. In this case study, the tipping tank location was simulated immediately upstream of the furthest house from the collection sewer. This location is identified on Figure 1(b) with the blue letter 'T' in the north west corner.

2.5 Methodology

In summary, the overall approach was to simulate the performance of the Waulkmill Development in terms of solid transport distances with standard fittings, then to reduce the water consumption figures to represent water conservation measures implementation, and repeat. A third iteration involved the use of a tipping tank added to the system, to determine it's effectiveness. Within this process, the water conservation reductions of 80% and 60% were applied to w.c.-only, shower-only, and w.c. + shower. This was done to determine the most influential combination. The overall aim is to propose a system capable of safely conserving water down to 60% of non-conserved consumption rates. The simulations were limited to these appliances as the impact of reducing the flow from other appliances (basins and white goods) had very little impact on flow energy and solid transport characteristics.

III. Results

3.1 Overview

Results are presented in terms of carry distance of solids. Although a wide range of flow parameters are available as output from DRAINET, the carry distance data is arguably the most important and it is also the easiest to interperet. On Figure 1(b), the houses chosen to have tracking of solid positions are marked with the yellow numbers 1, 2, 3 and 4. All graphs have simulation or run numbers below them, identifying the actual appliance configuration and simulation number out of a total of 56 for this investigation. Some simulation numbers appear more than once in order to present baseline data for comparison.

3.2 Water Conservation Permutations

The results of conserving w.c. and shower output singly and in combination, in terms of solid travel distance, are shown below.

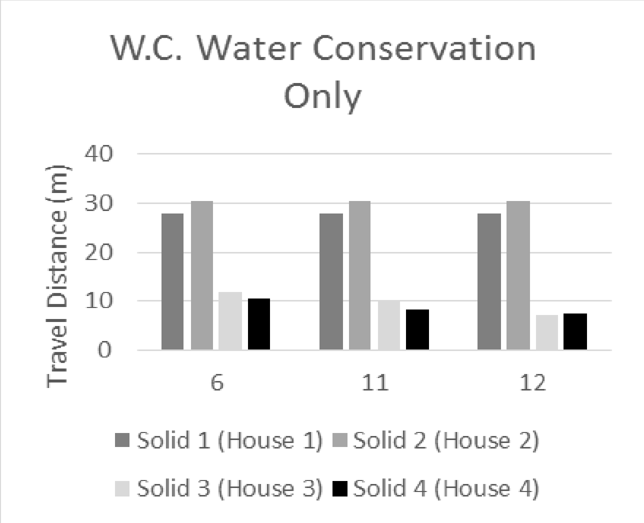

Figure 4 Solid travel distance for runs allocated to w.c. water conservation only

It can be seen from Figure 4 that there was no significant reduction in the overall travel distance by the two of the four solids as the w.c. operating capacity dropped from 100% (run 6) to 80% (run 11) and then 60% (run 12).

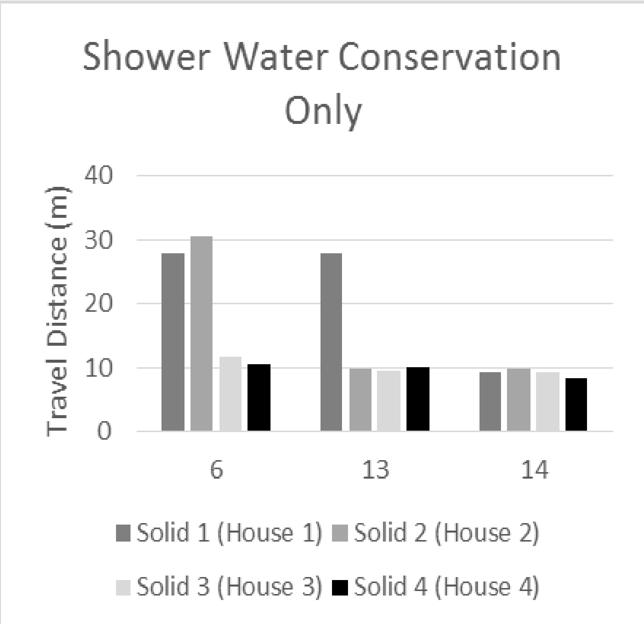

Figure 5 Solid travel distance for runs allocated to w.c., shower and basin water conservation only

From Figure 5, unlike the w.c., a reduction in the shower operating capacity from 100% (run 6) to 80% (run 13) appears to significantly affect the travel distance of Solid 2. It reduces from approximately 31m to 9m and a reduction in solids 3 and 4 travel distance is also evident. When the shower operates at 60% capacity (run 14), all four solids experience a reduction in travel distance.

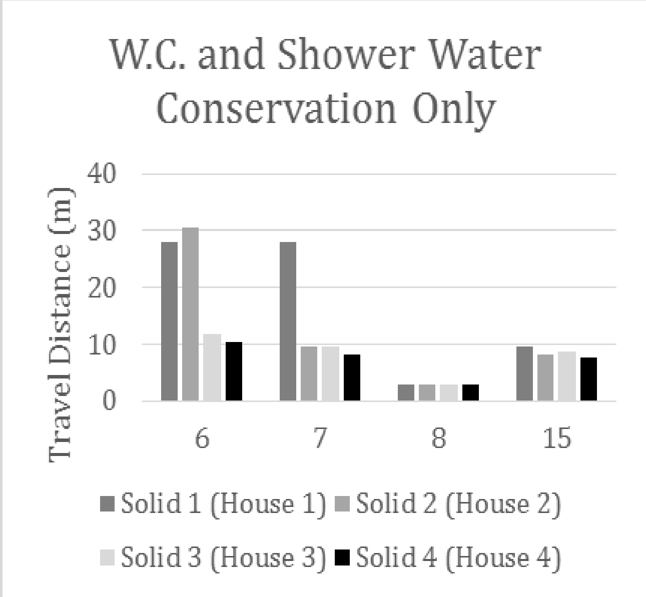

Figure 6 Solid travel distance for runs allocated to w.c. and shower water conservation only

Figure 6 shows the baseline data (run 6). A reduction in the operating capacity of the showers alongside the w.c. culminates in a loss of travel distance for the solids as follows: w.c. 60% + shower 80% (run 7); . w.c. 60% + shower 60% (run 8); w.c. 80% + shower 60% (run 15). Other permutations had intermediate results and have been omitted for brevity.

3.3 Tipping Tank Usage

The appliances and their characteristics used in the simulation of the tipping tank runs matched those in Section 3.2 above.

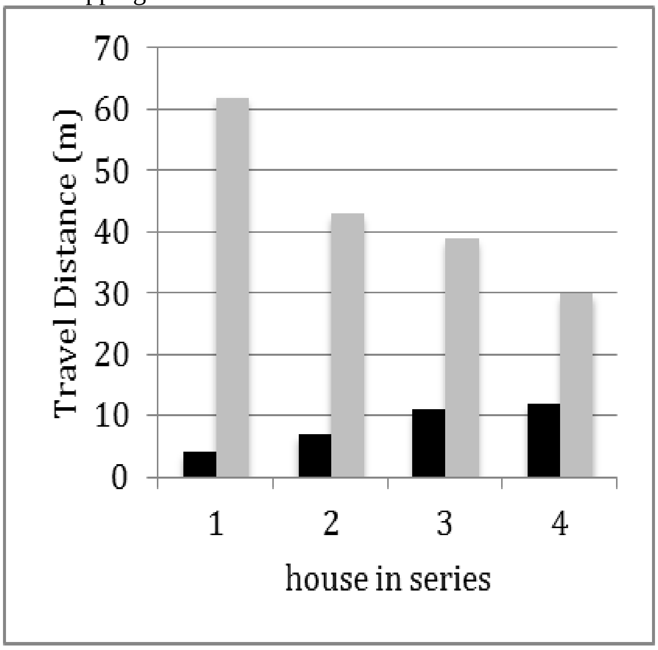

Figure 7 Solid position vs system end for each solid with water use at 60%

Figure 7 is based on 60% water use compared to standard for w.c. and shower, and illustrates the travel distance of the solids that enter the system from the house numbers on Figure 1(b) (blue) against the distance traveled when the tipping tank is employed (red).

IV. Discussion

Unlike the Single House and Double House simulations, only 2 types of appliances would experience a reduction in capacity/water conservation methods: w.c.'s. and showers. The reasoning for this was based simply on the fact that variation in the basin's capacity was practically negligible in previous runs. This is also observable on the full scale test system employed by the author: once solids have deposited, trickle flows are not sufficient to refloat them and displace them. Another alteration to the testing during these runs was that all w.c.'s and showers' within the simulated layout would operate at the same capacity. For example, all w.c.'s would be set at either 100%, 80% or 60% in all four of the houses. This significantly reduced the possible combinations for the simulations. This means that the data is courser than could have been achieved, but it was adequate for the scope of this investigation.

The solids travel the least distance when the w.c. and showers are all operating at the minimum capacity of 60%. There is only a slight reduction in the travel distance for solids 3 and 4 when the w.c. capacity is lowered to 80% and then 60%. The reason for this is because each solid travels enough distance to enter the communal discharge pipe and there is enough shear force from the remaining discharging appliances to carry it out the DRAINET system. Run 3 is different as the discharge from the 60% w.c. capacity is not enough to allow either solid to be transported to the communal discharge pipe where it can then be picked up by the flow from House 2. This results in a blockage.

It should be remembered that solid position can also be observed with time, for example, as shown in Figure 8. In figure 8, the numerous small steps in the traces for each solid shown in Figure 6. Horizontal lines represent a stationary solid, while sloping lines (sometimes almost vertical) represent solid acceleration due to a discharge peak from a discharging appliance. From Figure 8, the movement of all four solids that enter the w.c.'s during the simulation with each appliance operating at 100% initially travel 3.1 metres in approximately 4 seconds before remaining stationary in the system for some time. The reason for this can be attributed to the flush of the w.c. carrying the solids. The solids are then picked up at around 400 seconds into the simulation and whilst the solid in House 1 eventually travels 28m, thus leaving the system, the solid in House 3 merely travels a total of 12m. Both were able to be regain motion as they were situated in the main pipe following the first flush and a sudden discharge of water, from the second flush of the w.c.'s, has then pushed the solids further down the system before they remained stationary again. Another surge of water occurs around the 500 second mark and the solids are carried approximately a further 3 metres.

A reduction in the capacity of the w.c. and/or the showers resulted in a reduction in the travel distance of all solids. The maximum travel distance recorded for each solid would suggest that the system deposits solids within the communal discharge pipe even when the appliances are all operating at 100%. The solid deposition when the w.c.'s and showers are all operating at 60% suggests that each solid does not travel far enough to reach the communal discharge pipe and so cannot be picked up by any downstream discharge.

From previous research experience [12], [13], stranded solids are likely to remain stranded while subsequent fluid-only discharges swirl around them. Accretion of subsequent solids during mixed-content flushes will occur, resulting in very low accumulated solid transport velocity and therefore unusually long transit times. This will also reduce the normal solid break up attributed to transport, further exacerbating the effect.

In order to test the theory that the tipping tank is an effective mitigation strategy and only uses a small percentage of the conserved water, a 14.1 litre tipping tank was simulated discharging into the folly operational system (i.e. one in which stranded solids were already present. Figure 7 shows that with the tipping tank, there is a significant increase in solid transport distance from all four sample houses. According to WaterWise and design guides [14] , the current domestic consumption rate is approximately 150 litres per person per day. Even if only 50 litres of this is attributed to the w.c. and shower, then in the 32 houses simulated in this investigation, a total of 1,600 litres would be saved each day if those appliances were operated at 60% capacity. A conservative fraction of 10% of this saving would allow the tipping tank employed to be activated once every two hours, providing more than enough additional energy to result in all stranded solids being cleared from the common collection drain.

V. Conclusion

The testing undertaken in this investigation focuses on the reduction in solid transport distance within a water distribution system when the amount of throughflow is reduced. When this throughflow is reduced significantly (60% operating capacity) the introduction of a tipping tank ensures the solid transport distance is increased. For example, a reduction in all of the major water appliances used to 60% operating capacity meant a reduction of approximately 1,600 litres of water throughout 31 houses over the course of a day, but deposition occurred frequently in the system and this was cummulative. By utilising a tipping tank with a capacity of 14.1 litres and 11 tips per day (just 10% of the water that has been saved from the appliance capacity reduction), there are no blockages and 90% of the 1,600 litres of the water conservation (1440 litres) is still achieved.

This appears to be a logical solution to improving water conservation as the tipping tank yields positive results in testing. However, the practicality of positioning a tipping tank so that it maximises water conservation within a system is an issue that would probably need site-by-site evaluation. Furthermore, the exact operating capacity and method for refilling the tipping tank must be thoroughly investigated before it can be deemed a viable option. A small range of sizes, perhaps 20 litres and 50 litres, and strategic locations of every 20 or 50 homes and a tip frequency of once every twenty-four hours, for example, may be quite reasonable. A simple sizing chart in the form of a nomogram would be sufficient for this purpose, and easily incorporated into code guidance. This solution appears to offer a feasible solution that can be implemented quickly, allowing water conservation measures to be taken that would otherwise lead to increased solid deposition. This has the greatest potential to allow the mission and vision of the Waterise, by helping to mainstream water efficiency across the UK and enabling significant water efficiency compared to current levels which is economically viable and environmentally beneficial.

The positioning of the tipping tank may influence the system's performance. For example, the 5 litre tipping tank may be effective it is positioned closer to the terraced houses' outlet. Further simulations should be conducted to determine whether more than one tipping tank should be included in such a system and if the strategic placement of two 5 litre tipping tanks is more beneficial than a single 20 litre tipping tank, for example.

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